Air, ground, and groundwater recharge temperatures in an alpine setting, Brighton Basin, Utah

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[1] Noble gases are useful tracers for constraining groundwater recharge temperature and elevation, critical in determining source areas of groundwater recharge in mountainous terrain. A monitoring network in the alpine Brighton Basin in the Wasatch Mountains of northern Utah, USA, was established to examine the relationship between air temperatures, ground temperatures, and noble gas groundwater recharge temperatures. Maximum noble gas groundwater recharge temperatures computed using the closed-system equilibration model from 25 samples collected over the 2 year period 2007 to 2009 averaged 2.9 ± 1.2°C, within the experimental error of the mean ground temperature of 2.3°C measured within the probable recharge area. Maximum noble gas recharge temperatures vary from 0 to 7°C, also comparable to ground temperature variations in the region. Groundwater ages in the collected samples vary from 0 to 7 years indicating changing flow paths to the collection site during the experiment. Mean ground temperatures in the upper 1 m of soil over the 2 year time period is 2.3°C, which is 1°C cooler than the mean surface air temperature extrapolated from a nearby meteorological station. This comparison contradicts an earlier observation that mean annual ground temperatures in central Utah are generally warmer than air temperatures. The offset in the Brighton Basin is explained by modeling a snow effect on ground temperature. This detailed study suggests that interpretation of groundwater recharge temperatures derived from noble gases should be attentive to the complex local ground temperature effects in the recharge areas.

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1. Introduction

[2] Determining sources of recharge to aquifers is becoming increasingly important as demands on groundwater continue to increase. One such area where water demands are increasing at a rapid rate is the intermountain west of the U.S. Intermountain basin-fill aquifers and underlying permeable bedrock aquifers are a significant source of groundwater in these arid and semiarid regions. Existing studies [*Anderson and Freethey*, 1996; *Gates*, 1995; *Manning and Solomon*, 2003; *Mason*, 1998; *Prudic and Herman*, 1996] have shown that water sourced in the adjacent mountain blocks accounts for one third to nearly all of the groundwater recharge to these basins. Accurate estimations of the amount of mountain-block recharge to these aquifers are important for water resource management planning.

[3] Several studies [*Aeschbach-Hertig et al.*, 1999; *Ballentine and Hall*, 1999; *Manning and Caine*, 2007; *Manning and Solomon*, 2003; *Mazor*, 1991; *Rauber et al.*, 1991; *Zuber et al.*, 1995] have shown noble gases to be useful traces for examining groundwater recharge temperature (T_r) and elevation (H), which in turn can be used to determine source areas of groundwater recharge to the intermountain aquifers. In order to constrain both recharge temperatures and elevations, however, a recharge temperature versus elevation curve (T_r lapse curve) must be developed for the area in question [*Aeschbach-Hertig et al.*, 1999; *Manning and Solomon*, 2003].

[4] The variation of air temperature with elevation is well known from atmospheric science. An average environmental lapse rate is $-6.5°C\ km^{-1}$, intermediate between a dry adiabatic lapse rate of $-9.9°C\ km^{-1}$ and a saturated adiabatic lapse rate of $-5.0°C\ km^{-1}$. Studies by *Aeschbach-Hertig et al.* [1999] and *Zuber et al.* [1995] used T_r lapse curves that were developed assuming a consistent relation between T_r and the mean annual air temperature (T_a) at all elevations, either $T_r = T_a$ at all elevations [*Aeschbach-Hertig et al.*, 1999], or $T_r = T_a - 1°C$ at all elevations [*Zuber et al.*, 1995]. In these studies, the noble gas data were used to derive a set of best-fit pairs of H and T_r for each sample by specifying different values of assumed H and then solving for T_r and excess air. The most probable values of H and T_r for each sample were then determined by finding the point of intersection between the suite of best-fit solutions and the assumed recharge lapse curve. This technique was

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applied to a small number of samples with mixed results; for some samples the derived H values were reasonable, while for others the derived H values were inexplicably too high or too low.

[5] *Manning and Solomon* [2003] took a more rigorous approach to derive a local T_r lapse curve for the Wasatch Mountains of central Utah. In their study, dissolved noble gases were sampled in 16 springs and mine tunnels at various elevations within the mountain block, and a derived maximum and minimum T_r for each sample was determined using constrained minimum and maximum H values particular to each sampling site. *Manning and Solomon* [2003] then used the derived T_r and H data to develop a T_r lapse curve for the Wasatch Mountains using a least squares linear regression. Their T_r lapse curve has a similar slope ($-7.3°\mathrm{C\ km}^{-1}$) to the atmospheric lapse rate (for adiabatic cooling) in the Wasatch Mountains ($-6.4°\mathrm{C\ km}^{-1}$); however, it is approximately 2 to 4°C cooler than the atmospheric lapse curve (Figure 1). Based on all derived minimum and maximum values of T_r, *Manning and Solomon* [2003] concluded that, on average, T_r was about 2°C cooler than T_a within the Wasatch Mountains. Due to the lack of wells in high alpine recharge areas within the Wasatch Mountains, however, *Manning and Solomon*'s [2003] derived recharge lapse curve was never ground-truthed; that is, *Manning and Solomon* [2003] did not measure ground (water table) temperatures in recharge areas to confirm that they were in agreement with the noble gas derived recharge temperatures.

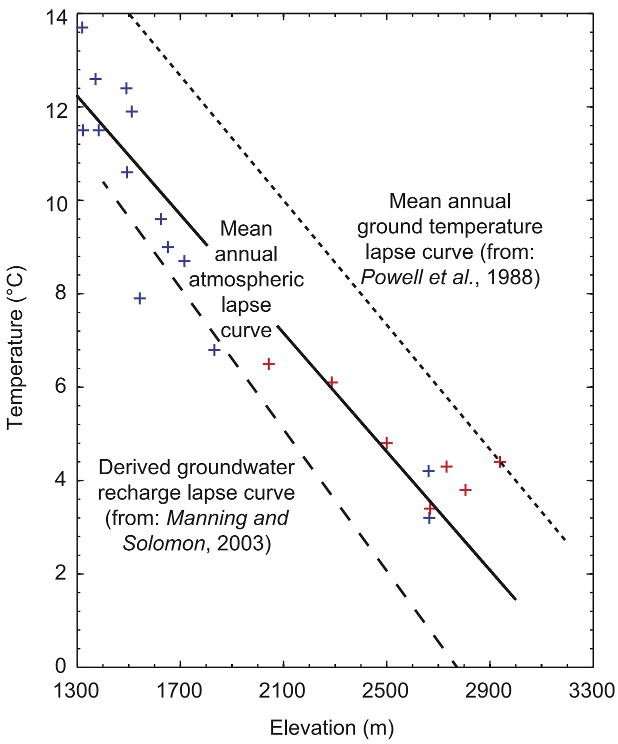

Figure 1. Lapse rates of temperature versus elevation in northern and central Utah. Shown are the mean annual atmospheric lapse curve for the Wasatch Mountains (solid line) derived from SNOTEL (red crosses) and Western Regional Climate Center (blue crosses) meteorological station data; groundwater recharge lapse curve from *Manning and Solomon* [2003] for the Wasatch Mountains (dashed line); and mean annual ground temperature lapse curve for sites in central Utah from *Powell et al.* [1988] (dotted line).

[6] The observation that *Manning and Solomon*'s [2003] derived T_r lapse curve is cooler than the atmospheric lapse curve for the Wasatch Mountains is significant in many respects. Generally, shallow water table (10–20 m depth) temperatures are approximately 1 to 2°C warmer than T_a [*Anderson*, 2005; *Domenico and Schwartz*, 1998], and mean annual soil temperatures can be biased 1 to 4°C higher than T_a [*Powell et al.*, 1988; *Putnam and Chapman*, 1996] (Figure 1). Studies by *Bartlett et al.* [2004, 2005], *Cey* [2009], and *Smith et al.* [1964] have also shown that in areas of prolonged snow cover mean annual ground temperatures may be warmer than T_a as the snow insulates the ground from colder winter air temperatures. *Cey* [2009] has furthermore used numerical simulations to explore the effects of precipitation, water table depth and air temperature variations on mean water table temperatures during groundwater recharge.

[7] Alternatively, under some circumstances snow cover and snow melt may produce cooler mean annual ground temperatures than mean annual air temperatures. *Bartlett et al.* [2004, 2005] show that while snow may insulate the ground from cooler air temperatures during the winter, persistent snow cover in late spring may pin the ground temperature near 0°C while air temperatures warm during the spring and early summer, producing mean annual ground temperatures that are cooler than T_a. Additionally, as snow melt is often the main source of recharge in mountainous terrain, large volumes of snow melt infiltrating fractured rock may keep temperatures in the unsaturated zone and water table near 0°C, especially as water table depths may decrease to less than 3 m depth during spring snow melt events [*Buttle*, 1989; *Hill*, 1990; *Klump et al.*, 2006]. Consequently, in many high alpine areas, T_r could be considerably lower than T_a.

[8] To determine why recharge temperatures within the Wasatch Mountains are apparently cooler than mean annual air temperatures, this study investigates the relation between air, ground and groundwater recharge temperatures within the Brighton Basin, a high alpine basin located within the Wasatch Mountains. The area chosen within the Brighton Basin is considered to be an ideal location for several reasons: (1) installation of a shallow monitoring well at a local discharge site where groundwater levels are near land surface was possible; (2) recharge areas within the basin are constrained by the topography of the basin, and span only about a 100 m difference in elevation; they cannot be lower than the elevation of the discharge site at 2770 m and cannot be much higher than about 2890 m where there is break in slope between the basin and the peaks surrounding the basin as it is highly unlikely that groundwater recharge is occurring at the top of the peaks surrounding the basin; and (3) the topographic map shows the selected sites to exist in a small sub-basin, which further limits the location of the probable recharge area contributing water to the discharge site (Figure 2). Other sub-basins exist northeast and southwest, likely with groundwater flow regimes separate from the sampling sites.

[9] A monitoring network within the basin was used to compare air, ground, and groundwater recharge temperatures

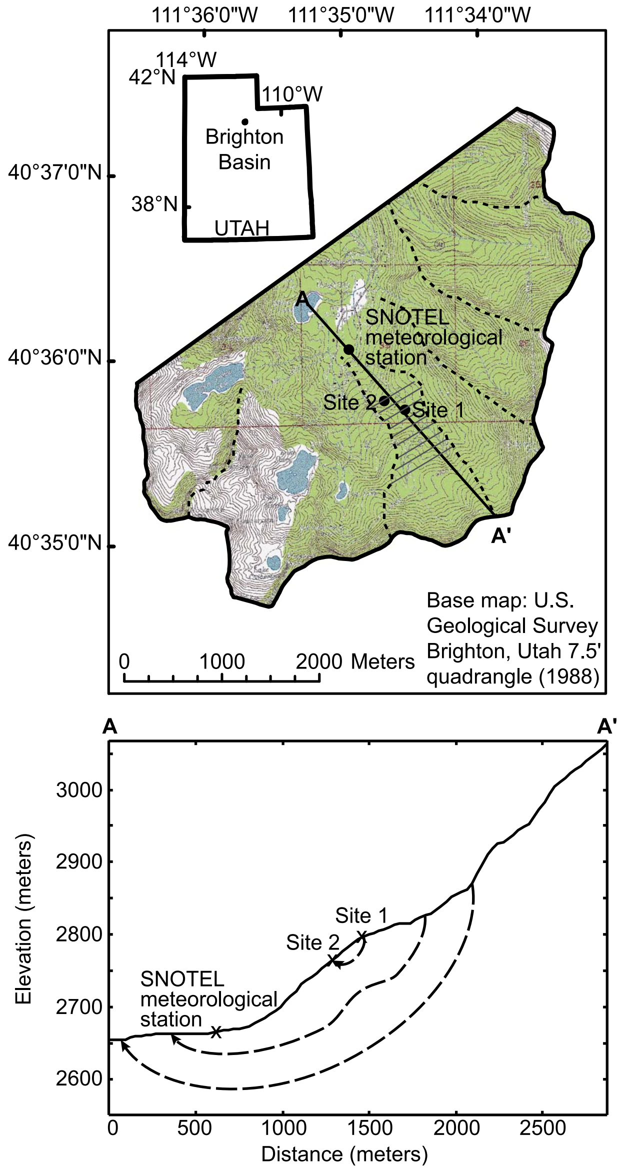

Figure 2. (top) Map of land-surface topography of the Brighton Basin, Utah, and locations of monitoring sites. Dotted lines delineate sub-basins, and hatchured area represents the probable recharge area for the monitoring sites. (bottom) Two-dimensional cross section of land-surface topography and conceptualization of possible groundwater flow paths (dashed lines) within the basin.

and groundwater ages over a period of more than 2 years. Air temperature and snow depth data were drawn from a meteorological station within the basin that is part of the SNOTEL network. Ground temperatures at multiple depths were continuously monitored using temperature probes that were installed at local recharge and discharge areas within the basin. Groundwater temperatures within a shallow well in the discharge area were also continuously monitored. Noble gas and tritium samples from the well were generally collected every 2 to 8 weeks to determine groundwater recharge temperatures and groundwater ages.

[10] This study had three objectives. First, the data collected from the monitoring network were used to examine how the noble gas recharge temperatures relate to ground and air temperatures. Second, the data were used to identify possible seasonal effects in the groundwater recharge temperatures, ages, and flow regime within the basin. And third, the data were used to validate, at least at one point, the derived recharge lapse curve developed by *Manning and Solomon* [2003]. Validation of this lapse curve has implications for using noble gases collected from discharge areas within mountainous terrain to develop a recharge lapse curve, and application of this approach in a variety of high alpine terrains.

2. Site Description and Monitoring Network

2.1. Site Description

[11] The connection between air, ground, and groundwater recharge temperatures was investigated by establishing a monitoring network within the Brighton Basin, a high alpine basin located at the head of Big Cottonwood Canyon within the Wasatch Mountains (Figure 2). The Wasatch Mountains are located to the east of the Salt Lake Valley in northern Utah and form the eastern margin of the Basin and Range physiographic province. The Brighton Basin ranges in elevation from 2650 m (8700 ft) to over 3200 m (10,500 ft). The peaks surrounding the basin to the north and east are Tertiary igneous intrusions of the Alta and Clayton stocks, and form the divide between the headwaters of Big Cottonwood Creek on the west and Pine Creek on the east [*Stokes*, 1986]. The basin was carved by glaciation, and as a result the basin contains many small glacial moraines.

[12] Mean annual precipitation in the Wasatch Mountains ranges between 50 to 130 cm [*Manning and Solomon*, 2003]; most of this precipitation falls as snow. The Brighton Basin receives an average of 1270 cm (500 inches) of snow per year. Groundwater recharge in the basin is mainly derived from snowmelt that infiltrates into fractures in the bedrock of the Alta and Clayton stocks, or through the unconsolidated glacial deposits. Groundwater discharge in the basin is to small springs, streams, lakes, and evapotranspiration.

2.2. Monitoring Network

[13] Air temperature and snow depth data were drawn from a preexisting SNOTEL meteorological station (SNOTEL site: Brighton, Utah; Site number: 366), located at an elevation of 2667 m (8750 ft) within the basin. Multidepth ground temperature probes were installed in two locations within the basin. The first probe was installed in a small glacial moraine (site 1) at an elevation of approximately 2790 m within the probable recharge area. The second probe was installed in a wetland/bog type discharge area (site 2) approximately 230 m downgradient from the glacial moraine, at an elevation of approximately 2770 m. These probes (also known as MRC probes, constructed by Geneq) consist of a string of precision thermistors epoxied into a single, 109 cm long rod. Five thermistors placed at 7, 12, 22, 52, and 102 cm from the top of the probe were used to measure ground temperatures.

[14] Water temperatures were continuously monitored at a shallow well installed in the wetland area near the probe at site 2 using a HOBO Water Temp Pro v2 Logger (developed by Onset). The well was constructed using 2-inch diameter PVC tubing with a 30-inch length screen. The bottom of the

well is located approximately 1.6 m below land surface. The logger was suspended from the well cap so that it was positioned at approximately the middle of the well screen.

[15] Groundwater recharge temperature and age were determined using noble gas and tritium samples that were collected periodically at the well. Noble gas samples were collected using passive diffusion samplers similar to those shown in *Sanford et al.* [1996]. The samplers were allowed to equilibrate within the well water for at least 24 h. The gases were then measured using a quadrapole mass spectrometer at the University of Utah noble gas laboratory, and from these measured gases a groundwater recharge temperature was determined (see section 3.4 below). Tritium samples were collected in 1 L plastic bottles, and were used to determine the apparent groundwater age using the tritium/helium-3 ($^3H/^3He$) dating method [*Solomon and Cook*, 2000].

3. Data

3.1. SNOTEL Meteorological Station Data

[16] Air temperatures and snow depth were measured at the Brighton meteorological station that is part of the SNOTEL network. Data from this station are archived on the SNOTEL website which can be accessed at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=366&state=ut. The station has been in operation since 1 October 1985, and has been recording hourly air temperatures since 31 January 1996; before this date, air temperatures were recorded only one to four times per day. Snow depth at the station has been measured hourly since 7 October 1997. Data from the period of March 2007 to March 2009, which encompasses the period of noble gas sampling and ground temperature monitoring, are shown in Figures 3–5 and summarized in Table 1.

3.2. Ground Temperature Data

[17] Ground temperatures were measured at multiple depths up to 1 m at two locations within the basin, using the MRC probes in conjunction with Campbell Scientific CR-10 data loggers. At both locations, thermistors on the probes were sampled every 60 s, and the mean of 30 measurements were stored every 30 min. At site 1 the MRC temperature probe was installed on 3 February 2007 in a glacial moraine within the probable recharge area. Ubiquitous subsurface cobbles prevented full penetration of the probe at this site; only two thermistors, therefore, were located below ground at 22 and 72 cm depth, respectively. The water table at this site was not intersected during installation of the probe; however, the soil near the bottom of the hole into which the probe was inserted was very moist, suggesting that the water table at this site was only slightly deeper than 79 cm at the time of installation. At site 2 the MRC temperature probe was installed on 24 February 2007 in a bog/wetland (discharge) area approximately 230 m downgradient from the glacial moraine and site 1. At this site, the land surface was constantly saturated suggesting that the water table was at, or slightly above, land surface. At site 2, it was possible to install the probe to a depth of 104 cm, so all five thermistors were below ground at 2, 7, 17, 47, and 97 cm depth. Data for the two probes from the period of March 2007 to March 2009 are shown in Figures 3 and 4, and summarized in Table 1.

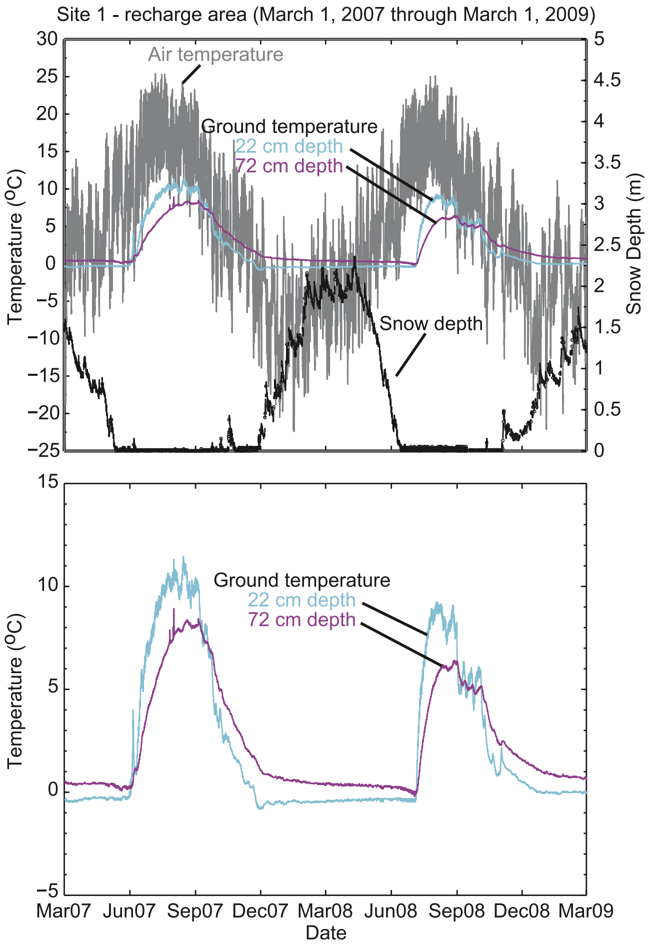

Figure 3. Relation of ground temperatures at site 1 (recharge area) to air temperatures and snow depth. (top) Hourly mean air temperature and snow depth data from the SNOTEL meteorological station, and 30-min mean ground temperature data at site 1, Brighton Basin, Utah; (bottom) enlargement of the 30-min mean ground temperature data at site 1.

3.3. Groundwater Temperature Data

[18] In addition to ground temperatures, groundwater temperatures within a shallow well installed in the discharge area (site 2) near the MRC probe were measured using a HOBO temperature logger. The sensor was suspended from the well cap to a depth of approximately 1.2 m (middle of the well screen); temperatures were logged at 30-minute intervals and periodically downloaded throughout the study. The logger in the well was deployed on 31 March 2007. Groundwater temperatures for the period March 2007 to March 2009 are shown in Figure 5 and are summarized in Table 1.

3.4. Noble Gas Groundwater Recharge Temperature Data and Age Data

[19] Noble gas samples for the determination of groundwater recharge temperature and tritium samples for the determination of groundwater age were generally collected every two to eight weeks from 6 February 2007 to 25 May 2009 from the well. Groundwater recharge temperature and

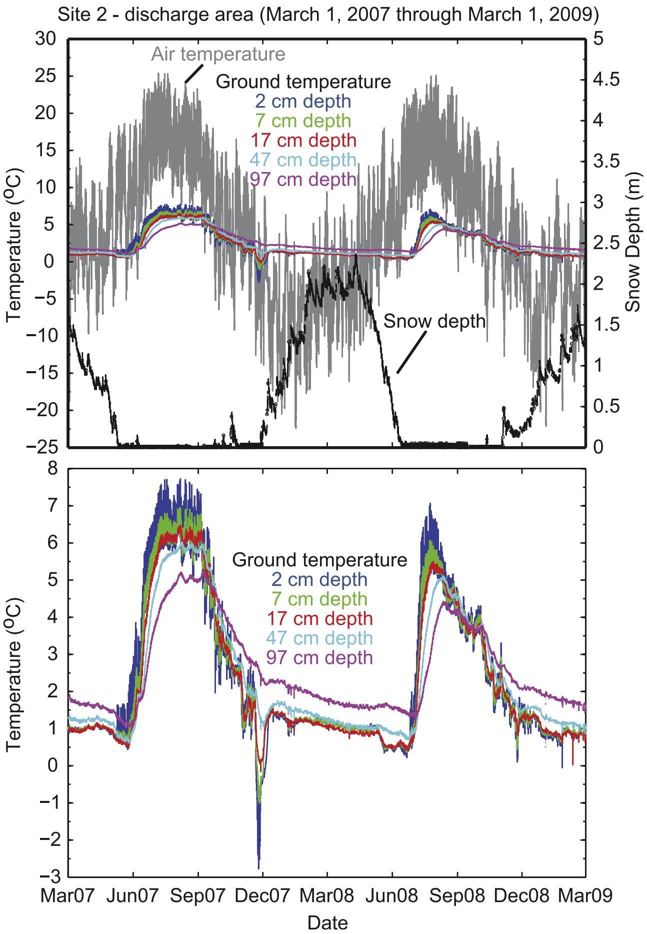

Figure 4. Relation of ground temperatures at site 2 (discharge area) to air temperatures and snow depth. (top) Hourly mean air temperature and snow depth data from the SNOTEL meteorological station, and 30-min mean ground temperature data at site 2, Brighton Basin, Utah; (bottom) enlargement of the 30-min mean ground temperature data at site 2.

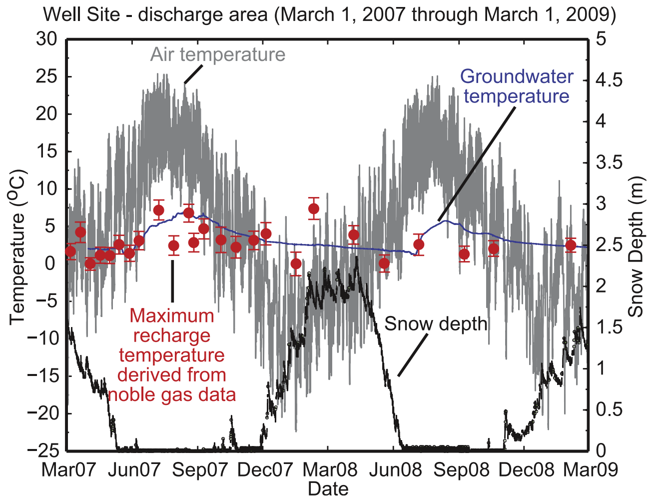

Figure 5. Relation of groundwater temperatures from the well at site 2 (discharge area) and groundwater recharge temperatures to air temperatures and snow depth. Shown are hourly mean air temperature and snow depth data from the SNOTEL meteorological station, 30 min groundwater temperature data from the well, and maximum groundwater recharge temperatures derived from noble gas samples collected from the well, Brighton Basin, Utah.

age data from the well are shown in Figures 5 and 6, respectively, and are summarized in Table 2.

[20] Currently, there are several models that are used in the determination of recharge temperatures from noble gas data, which differ in the way in which the "excess air" component is treated; these include the total dissolution (TD) model [*Andrews and Lee*, 1979; *Stute and Schlosser*, 1993], the partial re-equilibration (PR) model [*Stute et al.*, 1995], the closed-system equilibration (CE) model [*Aeschbach-Hertig et al.*, 2000; *Ballentine and Hall*, 1999], the multistep partial re-equilibration (MR) model [*Kipfer et al.*, 2002], the partial degassing (rism diopters (PD)) model [*Lippmann et al.*, 2003], the negative pressure (NP) model [*Mercury et al.*, 2004], the oxygen depletion (OD) model [*Hall et al.*, 2005], and the gas diffusion relaxation (GR) model [*Sun et al.*, 2008]. This study uses the CE model for the determination of recharge temperatures from the noble gas data. The purpose of this study was not about comparing results from the different excess air models, but rather about comparing noble gas derived groundwater recharge temperatures with groundwater table temperatures. The consistency between the mean model results and the mean groundwater table temperatures measured within the Brighton Basin suggests that the CE model adequately represents conditions within the basin.

[21] Measured noble gas and tritium concentrations are given in Table 2. Using inverse modeling techniques as described by *Aeschbach-Hertig et al.* [1999], these gas concentrations were then used to determine the unknown parameters of recharge temperature, excess air, and the fractionation of the excess air; salinity and recharge elevation (pressure) were prescribed a priori as 0 and 2768 m, respectively. The inverse modeling technique uses a nonlinear least squares method that finds those values of the model parameters that minimize χ^2, which is the sum of the squared deviations between the modeled and measured concentrations, normalized to the respective experimental uncertainties [*Aeschbach-Hertig et al.*, 2002]. The reported 1σ (i.e., 1 standard deviation) uncertainties in the recharge temperatures and ages (Table 2 and Figures 5 and 6) were determined using Monte Carlo simulations whereby the measurement errors of the noble gas and tritium concentrations were varied.

4. Results/Discussion

4.1. Temperature Data

[22] The data collected from the monitoring network were used to examine how the air, ground, and noble gas groundwater recharge temperatures relate to one another. Additionally, the data were used to identify possible seasonal variations in the groundwater recharge temperatures and ages, which may point to seasonal changes in the groundwater flow regime within the basin. The data were also used to investigate the effects of snow cover on ground temperatures within the basin.

Table 1. Summary of Air, Ground and Groundwater Temperature Data[a]

	SNOTEL, SAT			Site 1		Site 2					Well
	Max.	Min.	Mean	GT 22 cm, Mean	GT 72 cm, Mean	GT 2 cm, Mean	GT 7 cm, Mean	GT 17 cm, Mean	GT 47 cm, Mean	GT 97 cm, Mean	GWT, Mean
						2007–2008					
Mar	14.0	−18.8	0.7	−0.39	0.43	1.00	0.99	0.96	1.24	1.70	2.29[b]
Apr	17.4	−9.2	2.7	−0.29	0.42	1.01	1.04	1.03	1.23	1.58	1.98
May	18.6	−6.0	7.5	−0.28	0.28	0.93	0.85	0.72	0.84	1.24	1.76
Jun	23.3	−2.3	13.4	4.14	2.22	4.03	3.75	3.24	2.63	2.26	3.45
Jul	25.4	8.7	17.2	9.43	6.23	6.32	6.21	6.00	5.45	4.47	5.62
Aug	24.1	6.3	15.6	10.20	8.00	6.40	6.30	6.16	5.86	5.04	6.59
Sep	21.7	−6.4	9.8	7.23	7.21	4.86	4.97	5.08	5.27	4.87	5.99
Oct	16.5	−9.2	4.5	2.48	4.07	2.82	2.88	2.89	3.30	3.76	4.46
Nov	12.1	−13.6	0.8	0.25	1.96	0.71	0.94	1.16	1.92	2.80	3.59
Dec	8.8	−20.5	−7.2	−0.55	0.81	1.06	1.30	1.28	1.54	2.26	2.91
Jan	6.3	−22.4	−7.4	−0.47	0.56	1.17	1.23	1.23	1.51	2.09	2.61
Feb	9.4	−17.3	−5.3	−0.47	0.43	1.21	1.21	1.13	1.34	1.87	2.51
annual mean	–	–	4.4	2.62	2.73	2.64	2.65	2.58	2.68	2.83	3.65[c]
						2008–2009					
Mar	7.7	−16.1	−3.6	−0.42	0.38	1.13	1.09	0.98	1.16	1.69	2.31
Apr	13.2	−15.7	−0.9	−0.38	0.34	1.02	0.99	0.88	1.05	1.59	2.06
May	18.0	−9.0	4.2	−0.34	0.29	0.74	0.76	0.72	1.00	1.60	1.85
Jun	22.5	−2.2	10.2	−0.35	0.18	0.52	0.57	0.57	0.85	1.47	1.60
Jul	25.0	6.7	16.1	5.21	2.55	4.46	4.27	3.90	2.99	2.29	3.81
Aug	25.1	3.2	14.8	8.41	6.01	4.85	4.88	4.88	4.81	4.19	5.50
Sep	19.5	−1.3	9.3	5.36	5.24	3.80	3.83	3.83	3.98	3.86	4.42
Oct	16.8	−10.7	4.6	2.45	3.68	2.59	2.64	2.69	3.01	3.24	3.83
Nov	12.6	−12.7	0.5	1.01	2.03	1.54	1.59	1.60	1.91	2.39	3.00
Dec	7.9	−20.2	−5.8	0.19	1.26	1.19	1.25	1.25	1.52	2.04	2.68
Jan	11.1	−22.1	−3.6	−0.02	0.85	0.79	0.86	0.87	1.21	1.83	2.47
Feb	7.8	−16.1	−3.8	0.00	0.73	0.90	0.92	0.85	1.10	1.69	2.29
annual mean	–	–	3.5	1.78	1.97	1.98	1.99	1.94	2.06	2.33	2.99

[a]SAT, surface-air temperature; GT, ground temperature; GWT, groundwater temperature.
[b]Value interpolated from differences in monthly data for 2008–2009 versus 2007–2008.
[c]Value calculated as mean of monthly mean data for 2007–2008.

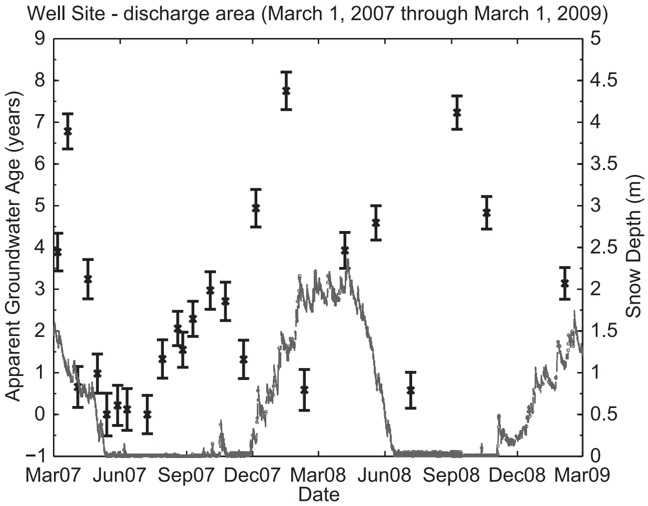

Figure 6. Age of groundwater samples (crosses) with 1 s.d. error bars collected from the well. Also shown are hourly mean snow depth data (gray line) from the SNOTEL meteorological station, Brighton Basin, Utah.

[23] Air temperatures for the period March 2007 to March 2009 varied between −22.4°C and 25.4°C (Table 1). Maximum temperatures occurred in July and August, while minimum temperatures occurred in January. Monthly mean air temperatures for March to September 2007 were 0.5 to 4.3°C warmer than monthly mean temperatures for March to September 2008. Conversely, monthly mean air temperatures for December to February 2007 to 2008 were 1.4 to 3.8°C colder than monthly mean temperatures for December to February 2008 to 2009. Monthly mean temperatures for October and November 2007 and 2008 were fairly similar, with differences of only 0.1 and 0.3°C. Annual mean temperature for the 2 years was 4.4 and 3.5°C, respectively. Because sites 1 and 2 are ∼100 m higher in elevation than the meteorological site where air temperatures are measured, there is about a 0.6°C offset in mean annual air temperatures (cooler) at sites 1 and 2.

[24] Ground temperatures at site 1 for the period March 2007 to March 2009 varied between −0.84 and 11.45°C at 22 cm depth, and between −0.21 and 8.91°C at 72 cm depth (Figure 3), while at site 2 ground temperatures varied between −2.77 and 7.72°C at the shallowest depth (2 cm), and between 1.04 and 5.22°C at the deepest depth (97 cm) (Figure 4). As expected, ground temperatures at both of these sites show less variation in minimum and maximum temperatures than air temperatures, with greater attenuation at greater depths. Additionally, ground temperatures at site 2 show less variation than ground temperatures at site 1. This difference is likely due to site 2 lying within a discharge area and groundwater flow through this site further dampens the annual variation in temperatures.

[25] At both site 1 and site 2, maximum ground temperatures generally occurred in July or August, lagging behind the timing of maximum air temperatures, with longer lag times occurring at deeper depths. For instance, at site 1, the deeper thermistor at 72 cm depth reaches its maximum temperature slightly later than the thermistor at 22 cm depth (Figure 3); the same can be seen at site 2 where maximum ground temperatures generally occurred in July for depths of 2, 7, and 17 cm, and in August at 47 and 97 cm depth (Figure 4).

[26] Minimum ground temperatures at the shallower depths at both sites (22 cm depth at site 1 and 2, 7, and 17 cm depth at site 2) generally occurred in late fall, just before the onset of snow cover (Figures 3 and 4). Minimum temperatures at the deeper depths (72 cm depth at site 1; and 47 and 97 cm depth at site 2) generally occurred in late spring/early summer during the annual snowmelt event. Additionally, ground temperatures at the shallower depths at both sites were warmer than temperatures at deeper depths from just after the disappearance of the snow cover through the summer months and into early fall; conversely, ground temperatures at the shallower depths were cooler than temperatures at deeper depths during the fall until just after the disappearance of the snow cover (Figures 3 and 4). Both the difference in the timing of the occurrence of minimum temperatures between the shallower and deeper depths, as well as the relative difference in temperatures between the shallower and deeper depths throughout the year shows that the shallower ground temperatures are more directly influenced by air temperatures, while the deeper ground temperatures are more directly influenced by groundwater flow.

[27] Annual mean ground temperatures at site 1 were up to 1.18°C colder than annual mean air temperatures (adjusted for elevation of site 1) for 2007 to 2008, and 1.12°C colder than mean annual air temperatures (adjusted for elevation of site 1) for 2008 to 2009 (Table 1). Similarly, annual mean ground temperatures at site 2 were up to 1.22°C colder than annual mean air temperatures (adjusted for elevation of site 2) for 2007 to 2008, and 0.96°C colder than annual mean air temperatures (adjusted for elevation of site 2 for 2008 to 2009). These results are consistent with the 2°C offset between mean annual air temperatures and groundwater recharge temperatures derived by *Manning and Solomon* [2003] for the Wasatch Mountains.

[28] Groundwater temperatures at the well for the period March 2007 to March 2009 varied between 1.10 and 6.89°C (Figure 5). Maximum temperatures generally occurred in August, attenuated and lagged slightly longer than 1 month after maximum air temperatures. Minimum temperatures occurred in either May 2007 or June 2008 during the annual snow melt event. Annual mean groundwater temperatures for 2007 to 2008 and 2008 to 2009 were 3.65°C and 2.99°C, respectively; this is slightly warmer than annual mean ground temperatures at both site 1 and site 2, and 0.75 and 0.51°C colder than the annual mean air temperature (adjusted for elevation of site 2) for the 2 years. The warmer temperatures at the well versus ground temperatures are likely due to the well measuring deeper temperatures (about 1.2 m depth), and/or from warm water moving up from depth that is typical of discharge areas.

4.2. Relation of Air and Ground Temperatures to Temperature at the Water Table

[29] Noble gas samples collected from the well at site 2 were used to calculate groundwater recharge temperatures, which essentially record the temperature at the water table. The noble gas recharge temperatures reported in this study were calculated at the altitude of the well screen, so they represent the maximum recharge temperatures possible, as

Table 2. Summary of Noble Gas Maximum Recharge Temperatures (T_r), Groundwater Ages, and Measured Noble Gas and Tritium Concentrations

Sample ID	Collection Date	Maximum T_r (°C)	Apparent Groundwater Age (years)	N_2 (ccSTP/g) $\times 10^{-2}$ Error: ±5.0%	^{40}Ar (ccSTP/g) $\times 10^{-4}$ Error: ±3.0%	^{84}Kr (ccSTP/g) $\times 10^{-8}$ Error: ±4.0%	^{20}Ne (ccSTP/g) $\times 10^{-7}$ Error: ±2.0%	^{129}Xe (ccSTP/g) $\times 10^{-9}$ Error: ±5.0%	^{4}He (ccSTP/g) $\times 10^{-8}$ Error: ±1.0%	R/Ra[a] Error: ±1.0%	^{3}H (TU) Error: ±5.0%
WA03	20070306	1.6 ± 1.1	3.9 ± 0.4	1.2	3.4	4.8	1.4	3.5	3.5	1.1	6.9
WA04	20070320	4.2 ± 1.4	6.8 ± 0.4	1.2	3.4	4.6	1.5	3.5	3.6	1.2	7.8
WA05	20070403	0.0 ± 0.8	0.7 ± 0.5	1.3	3.5	4.8	1.5	4.0	3.5	1.0	6.9
WA06	20070417	1.2 ± 1.1	3.2 ± 0.5	1.3	3.6	4.8	1.5	3.6	3.8	1.0	6.8
WA07	20070430	1.1 ± 1.1	1.0 ± 0.5	1.4	3.7	5.0	1.6	3.6	3.7	1.0	7.4
WA08	20070513	2.6 ± 1.2	0.0 ± 0.5	1.3	3.6	4.8	1.5	3.5	3.6	1.0	7.1
WA09	20070528	1.4 ± 1.1	0.2 ± 0.5	1.4	3.8	5.1	1.5	3.6	3.6	1.0	7.6
WB10	20070610	3.1 ± 1.2	0.1 ± 0.5	1.3	3.5	4.8	1.5	3.4	3.6	1.0	7.3
WB11	20070708	7.2 ± 1.3	0.0 ± 0.5	1.2	3.2	4.2	1.4	2.9	3.5	1.0	7.9
WA12	20070729	2.5 ± 1.3	1.3 ± 0.5	1.3	3.4	4.6	1.5	3.4	3.8	1.0	7.4
WA13	20070819	6.8 ± 1.2	2.1 ± 0.4	1.2	3.2	4.2	1.5	2.9	3.6	1.1	7.5
WA14	20070826	2.8 ± 1.2	1.6 ± 0.4	1.3	3.5	4.6	1.6	3.5	3.8	1.1	7.7
WB15	20070909	4.7 ± 1.3	2.3 ± 0.4	1.3	3.5	4.5	1.6	3.1	3.8	1.1	7.8
WA16	20071003	3.2 ± 1.7	3.0 ± 0.4	1.3	3.4	4.6	1.6	3.4	3.9	1.1	4.5
WA17	20071024	2.2 ± 1.4	2.7 ± 0.5	1.4	3.6	4.9	1.6	3.4	3.8	1.1	7.2
WA18	20071118	3.1 ± 1.2	1.3 ± 0.5	1.3	3.4	4.7	1.6	3.4	3.7	1.1	7.4
WA19	20071205	4.0 ± 1.5	4.9 ± 0.4	1.3	3.4	4.7	1.6	3.1	3.9	1.1	7.0
WA20	20080116	0.0 ± 1.6	7.8 ± 0.4	1.5	3.3	5.5	1.8	3.8	4.5	1.1	7.6
WA21	20080210	7.4 ± 1.4	0.6 ± 0.5	1.2	3.7	4.3	1.5	3.2	3.6	1.0	7.4
WA22	20080406	3.9 ± 1.2	3.9 ± 0.4	1.3	3.5	4.5	1.5	3.2	3.6	1.1	7.4
WA23	20080519	0.1 ± 1.1	4.6 ± 0.4	1.4	3.6	4.9	1.6	4.1	3.8	1.1	7.8
WA24	20080706	2.6 ± 1.4	0.6 ± 0.4	1.3	3.5	4.7	1.6	3.3	3.8	1.0	8.5
WA25	20080908	1.3 ± 1.0	7.2 ± 0.4	1.3	3.5	5.0	1.5	3.4	4.0	1.1	7.7
WB26	20081019	2.1 ± 1.0	4.8 ± 0.4	1.3	3.5	4.9	1.5	3.3	3.8	1.1	8.1
WB27	20090204	2.5 ± 0.9	3.1 ± 0.4	1.3	3.4	4.7	1.4	3.1	3.5	1.1	8.0

[a]R is the $^{3}He/^{4}He$ ratio of the sample; Ra is the $^{3}He/^{4}He$ ratio of air (1.384×10^{-6}).

it is unlikely that the well is receiving groundwater recharge at a lower elevation than the well screen.

[30] Groundwater recharge temperatures from noble gas samples collected between March 2007 and March 2009 ranged between 0.0 ± 1.6°C (16 January 2008) and 7.4 ± 1.4°C (10 February 2008), and averaged 2.9 ± 1.2°C (Figure 5 and Table 2), consistent with ground temperatures measured within the basin. Average maximum groundwater recharge temperatures were approximately 0.3°C warmer to 2.2°C cooler than annual mean air temperatures (adjusted for elevation of site 1) from 2007 to 2008, and were 0.0 to 1.3°C cooler than annual mean air temperatures (adjusted for elevation of site 1) from 2008 to 2009. These differences are comparable to the 2°C difference between groundwater recharge temperatures and mean annual air temperatures inferred by *Manning and Solomon* [2003] for the Wasatch Mountains.

[31] Groundwater recharge temperatures calculated from noble gas samples collected between March and December 2007, appear to track the groundwater temperatures measured at the well, following an attenuated and lagged annual temperature variation. This pattern is pronounced in 2007 with a range of 7°C between summer and winter samples. Apparent groundwater ages (Figure 6 and Table 2) from these same samples, however, varied between 0 and 7 years. This seasonal pattern in the noble gas recharge temperatures did not continue into 2008 and 2009 (Figure 5), with samples collected after December 2007 showing much more scatter, and no definitive seasonal trends. These data thus show general agreement between noble gas recharge temperatures and groundwater temperatures albeit with some complexity.

[32] Apparent groundwater ages from water collected between March 2007 and March 2009 at the well ranged between 0.0 ± 0.5 years and 7.8 ± 0.4 years (Figure 6 and Table 2). From March through December 2007, the apparent ages followed a seasonal pattern, with winter samples being 2 to almost 7 years older than late spring/early summer samples. This seasonal age variation points to possible variations in the groundwater flow regime throughout 2007. During times when there is little to no groundwater recharge (i.e., fall/winter) the well is capturing older groundwater. During high recharge times of the year (i.e., the annual snowmelt event during late spring/early summer) these older flow paths are pushed deeper within the aquifer, and are no longer being captured by the well; the well is capturing flow paths carrying younger water instead. It does not take much change in the depth of the flow paths to change which paths are being captured by the well; in fact, changes in depth as little as 20 cm may produce the seasonal pattern seen in the apparent age data in 2007. Like the noble gas recharge temperatures, the seasonal pattern in apparent age data did not continue into 2008 and 2009. The high scatter in apparent ages and noble gas recharge temperatures suggests that the groundwater flow regime within the Brighton Basin is quite complex, and warrants further study to explain the scatter within the data.

[33] Because the apparent age data suggest groundwater ranging up to 7.8 years, the air temperatures from 2000 to 2007 were also examined to determine differences between groundwater recharge temperatures and air temperatures for these older age samples. Annual mean air temperatures from 2000 to 2007 ranged between 2.9°C (2002 and 2004) and 4.6°C (2007), and averaged 3.5°C (data accessed from SNOTEL website at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=366&state=ut). Mean maximum groundwater recharge temperatures for the groundwater samples that show ages of being recharged before March 2007 were approximately 0.0 ± 1.2°C to 1.1 ± 1.2°C cooler than mean annual air temperatures from 2000 to 2007. Again, this is comparable to, to slightly less than, the 2°C difference between groundwater recharge temperatures and mean annual air temperatures inferred by *Manning and Solomon* [2003] for the Wasatch Mountains.

4.3. Snow Effects

[34] Comparison of changes in monthly mean ground and groundwater temperatures versus changes in monthly mean air temperatures over the 2 year study period illustrate the effects of snow cover on the ground temperatures within the basin. For example, monthly mean ground and groundwater temperatures for March through May 2007 are comparable to monthly means for March to May 2008 (differences of only 0.00 to 0.36°C), despite monthly mean air temperatures for March through May 2007 being approximately 3.3 to 4.3°C warmer than March through May 2008 (Table 1). This consistency in ground temperatures is likely due to snow cover insulating the ground from the air temperatures during these times of both years (Figures 3–5). Monthly mean ground and groundwater temperatures for June 2007 were 0.79 to 4.49°C warmer than monthly mean temperatures for June 2008 (Table 1); monthly mean air temperatures for June 2007 also were 3.2°C warmer than June 2008. The cooler ground temperatures in June 2008 may be attributed to the fact that (1) snow cover persisted one month longer in 2008 than in 2007 (Figures 3–5), resulting in insulating the ground from the warmer air temperatures for a longer period of time in 2008; and/or (2) air temperatures in June 2008 were cooler than air temperatures in 2007. While monthly mean air temperatures from July through September 2007 are only 0.5 to 1.1°C warmer than July through September 2008, monthly mean ground and groundwater temperatures from July through September 2007 are 0.85 to 4.22°C warmer than July through September 2008, with the largest differences occurring in July (Table 1). Again, this difference may be partly attributed to the snow cover in 2008 persisting longer in the spring and summer months, thereby preventing the ground from warming as much as in 2007 (Figures 3–5). And finally, monthly mean shallow ground temperatures for November to December 2007 are 0.13 to 0.83°C colder than monthly mean ground temperatures for November to December 2008 (Table 1). This is likely due to the later onset of snow in 2007 than 2008; in 2008, the onset of snow occurred nearly a month earlier than in 2007, thereby insulating the ground from the colder air temperatures for a longer period of time (Figures 3–5).

[35] The snow effects on mean annual ground temperatures were quantified using a numerical model of snow-ground thermal interactions developed by *Bartlett et al.* [2004, 2005]. *Bartlett et al.* [2004] found that snow onset time and duration were the two greatest controlling factors in determining whether the mean annual ground temperature is warmer or cooler than the mean annual air temperature. This temperature difference, called the "snow effect"

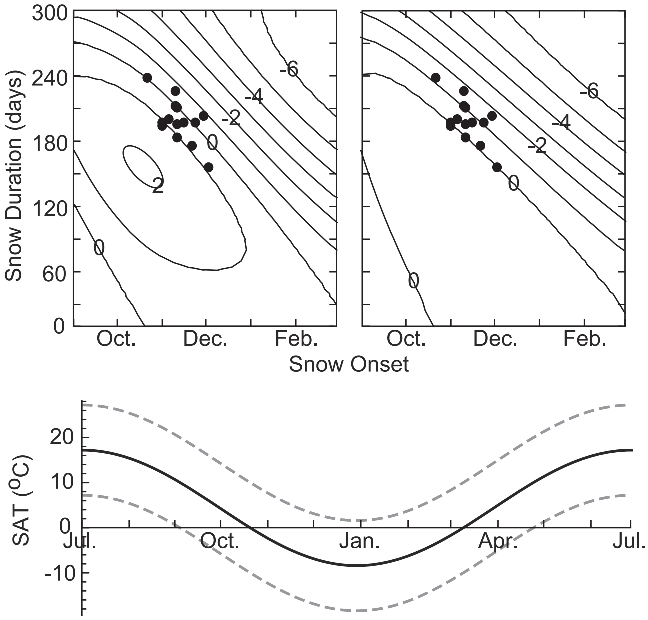

Figure 7. The snow effect-influence of snow event onset time and duration on mean annual surface ground temperatures relative to mean annual air temperatures. Contours illustrate the difference in°C between the mean annual surface ground temperature and the driving function (labeled SAT above). (top left) Results using an "air-filled" snow thermal diffusivity of 2×10^{-8} m^2 s^{-1}; (top right) results using an "ice-like" snow thermal diffusivity of 1×10^{-6} m^2 s^{-1}. The points represent snow onset and duration of annual snow events observed at the Brighton SNOTEL meteorological station from 1997 to 2011.(bottom) The annual driving function (solid line) and the limits of the diurnal fluctuations (dashed lines).

[*Bartlett et al.*, 2004], is plotted in terms of the controlling factors in Figure 7 for Brighton Basin, Utah. A snow season can either raise or lower the mean annual ground temperature relative to the air over an annual cycle. Warming of the mean annual ground temperature relative to air occurs when snow onset coincides roughly with the daily mean air temperature falling below 0°C, and lasting until daily mean air temperatures rise above the freezing point. During this time the ground is insulated by snow from the cold winter temperatures. Depending on the annual surface air temperature (SAT) cycle, this warming can be 2°C or greater. Alternatively, cooling of the mean annual ground temperature relative to air occurs when the snow onset is late and the duration is long, meaning that snow keeps the ground temperature pinned near 0°C, long after the daily mean temperature has risen above freezing.

[36] *Bartlett et al.*'s [2004] snow model uses inputs of both the annual and diurnal temperature cycles, as well as the diffusivity of the snow pack; however, the model assumes that the thermal properties (diffusivity) of the snow are homogenous and constant in both space and time. In actuality, the snowpack undergoes compaction due to melting and refreezing, which effectively changes the density and thermal properties of the snow as a function of time [*Bartlett et al.*, 2004]. Therefore, in order to capture the end members of the evolving snowpack and provide a constraint on the snow effect within the Brighton Basin, two simulations of the snow model were run; one with a thermal diffusivity of 2×10^{-8} m^2 s^{-1} which represents a "fluffy, air-filled" snow, and one with a thermal diffusivity of 1×10^{-6} m^2 s^{-1} which is representative of a more "ice-like" snow.

[37] Results from the snow model simulations are shown in Figure 7. Figure 7 (top left) shows model results for the thermal diffusivity of air-filled snow, and the top right panel shows the model results for the thermal diffusivity of more ice-like snow. Solid dots on Figure 7 indicate the onset time and duration for all annual snow events between 1997 and 2011 at the Brighton SNOTEL meteorological station, and indicate that the snow effect at Brighton is between +1.0°C and −2.0°C, with a mean snow effect of −1.0°C. This cooling is consistent with the measured ground, groundwater, and groundwater recharge temperatures within the basin.

5. Summary and Conclusions

[38] Although this study did not set out to evaluate noble gas thermometry comprehensively, it does provide details of the thermal regime of both groundwater recharge and discharge areas in an alpine setting. The thermal effects of snow cover in this setting are also studied. Using noble gas temperatures collected from groundwater samples within a discharge area that originates from a highly constrained recharge area, it is concluded that the noble gas recharge temperatures are consistent with surface ground temperatures within the probable recharge area, and that surface ground temperatures are cooler than mean annual air temperatures.

[39] To determine why groundwater recharge temperatures within the Wasatch Mountains are cooler than mean annual air temperatures, this study investigates the relation between air, ground, and groundwater recharge temperatures within the Brighton Basin, a high alpine basin located within the Wasatch Mountains. Hydrogeologic considerations of this site provide a tight constraint on the location and elevation of recharge areas. A pre-existing meteorological station from the SNOTEL network provided measurements of air temperatures and snow depth. Ground temperature probes were installed in both a local recharge and a local discharge area within the basin to determine the relation between air and shallow ground temperatures at these sites. Additionally, a well was installed in the discharge area that allowed for sampling of noble gases and tritium used to determine groundwater recharge temperature and age. Detailed monitoring over a 2 year period allowed identification of possible seasonal and annual signals in groundwater recharge temperatures and ages. Based on this monitoring, the following conclusions can be drawn:

[40] 1. Maximum noble gas groundwater recharge temperatures computed using the CE model from 25 samples collected from March 2007 to March 2009 in the Brighton Basin, Utah, at an elevation of approximately 2770 m, average 2.9 ± 1.2°C. This average is within the experimental error of the mean ground temperature of 2.28°C measured in the probable recharge area over the same time period.

[41] 2. The variation in noble gas recharge temperatures is from 0 to 7°C. This range is also comparable to ground temperature variations in the region throughout the annual cycle. In the first year of monitoring, the noble gas temperatures appear to follow an attenuated and lagged annual temperature variation similar to the ground temperatures, although the pattern is not replicated in the second year. Because apparent groundwater ages in the collected samples vary from 0 to 7 years, the groundwater flow pattern within the basin is likely complex and warrants further study.

[42] 3. Mean ground temperatures in the upper 1 m of soil at measurement sites 1 and 2 over the 2 year time period is 2.32°C. The ground temperature is 1.05°C colder than the mean SAT (adjusted for elevation of sites 1 and 2) of 3.37°C over the same period. This offset contradicts the trend of surface temperature variation with elevation (lapse rate) in central Utah, whereby ground temperatures are warmer than air temperatures; the offset, however, is explained by a snow effect where late spring and early summer snow cover cools the ground relative to air. Interpretation of groundwater recharge temperatures derived from noble gases, therefore, must be attentive to local ground temperature effects in the probable recharge zones.

[43] These conclusions indicate that in a snow dominated, high alpine area, such as the Brighton Basin, ground temperatures are cooler than air temperatures. The noble gas recharge data corroborate this fact, and the results are consistent with the 2°C difference between groundwater recharge temperatures and mean annual air temperatures inferred by *Manning and Solomon* [2003] for the Wasatch Mountains. This observation implies that in high alpine areas, the assumption that $T_r = T_a$ may not be valid. It appears that by utilizing noble gas recharge data from discharge points within the mountain block, a more appropriate T_r lapse curve can be derived for the area in question, thereby permitting a more correct interpretation of recharge altitude and, therefore, sources of recharge to the groundwater system.

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